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Full-Scale Field Test Results of the REAM Concept for Hard Rock Excavation

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PIFR-391

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J. D. Watson

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Advanced Research Projects Agency
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PHYSICS INTERNATIONAL COMPANY
2700 MERCED STREET • SAN LEANDRO, CALIFORNIA • PHONE 357-4610 (415) • TWX 891-9689 (415)

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13 ABSTRACT

This report describes the results of the full-scale field tests of the REAM concept for hard rock excavation. REAM is an innovative method of rock disintegration which utilizes the impact energy of high velocity projectiles to fracture and eject the rock. The concept was demonstrated by driving a 13-foot-diameter tunnel to a depth of 26 feet in a granitic rock formation at Hope Valley, California. The average mass of rock removed by the 10-pound concrete projectiles impacting at 5000 ft/sec was 3000 pounds. In addition to presenting the rock breakage data, this report discusses the characteristics of the impact ejecta, muck distribution, and wall contour control. The report is concluded with a preliminary economic and performance evaluation of the REAM concept in a high-speed tunneling application.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (cont.)

SECTION 1
INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

This report describes the work carried out under Bureau of Mines Contract Number HO220015, sponsored by the Advanced Research Projects Agency. The objective of this program was to demonstrate the REAM (Rapid Excavation And Mining) concept for excavation by driving a 13-foot-diameter tunnel into hard granitic rock.

REAM is an innovative method of rock disintegration which utilizes the impact energy of high-velocity projectiles to fracture and eject the rock. Inexpensive projectiles, such as concrete or steel cylinders weighing 10 pounds, are accelerated to velocities of more than 5000 ft/sec by conventional launchers. By firing a number of projectiles in a pattern, large amounts of rock can be excavated by the interaction of successive impacts.

In 1968 Physics International Company evaluated several technologies for their applicability to hard rock disintegration. Electron beams, lasers, water jets, and projectile impact were considered. The method of projectile impact was selected as the most promising innovative technique for rock disintegration because of its effectiveness, flexibility, and practicality. The rock is removed mechanically by a directed impact energy of nearly 4 million foot-pounds delivered at peak pressures of 2 million psi.

This application of energy is illustrated in Figure 1 which shows the projectile at the moment of impact. Because of the momentum of the projectile, the energy coupling to the rock is excellent, with the specific energy of the process being about 120 ft-lb/in.^{3} of rock removed. The projectiles are accelerated by conventional launchers which can operate on inexpensive chemical propellants. There is no standoff requirement for the launcher and it can be fired remotely, thereby making the integration of the launcher into a continuous mining or tunneling system relatively straightforward.

1.2 BACKGROUND

Before the full-scale field tests of the REAM concept were begun, the projected excavation rates of this method were based on the empirical scaling relation of impact craters in rock as put forth by Moore and Gault (References 1 and 2).

By scaling up the results of hypervelocity impact of projectiles weighing a few grams, it was concluded that projectiles weighing several pounds and impacting at velocities in the range of conventional guns would effectively excavate rock. For example, a 10-pound concrete projectile impacting at 5000 ft/sec would be expected to dislodge about 900 pounds of granite. Figure 2 shows the mass of rock ejected as a function of impact energy for single craters in a semi-infinite plane. Hydrodynamic scaling would predict that mass ejected is proportional to impact energy ($M_e \propto E_p$); however, the empirical fit to the data suggests that mass ejected is proportional to impact energy raised to the power 1.189 ($M_e \propto E_p^{1.189}$). The reason suggested for this scaling effect is that the effective target strength is apparently reduced with increased size of the area effected. Physics

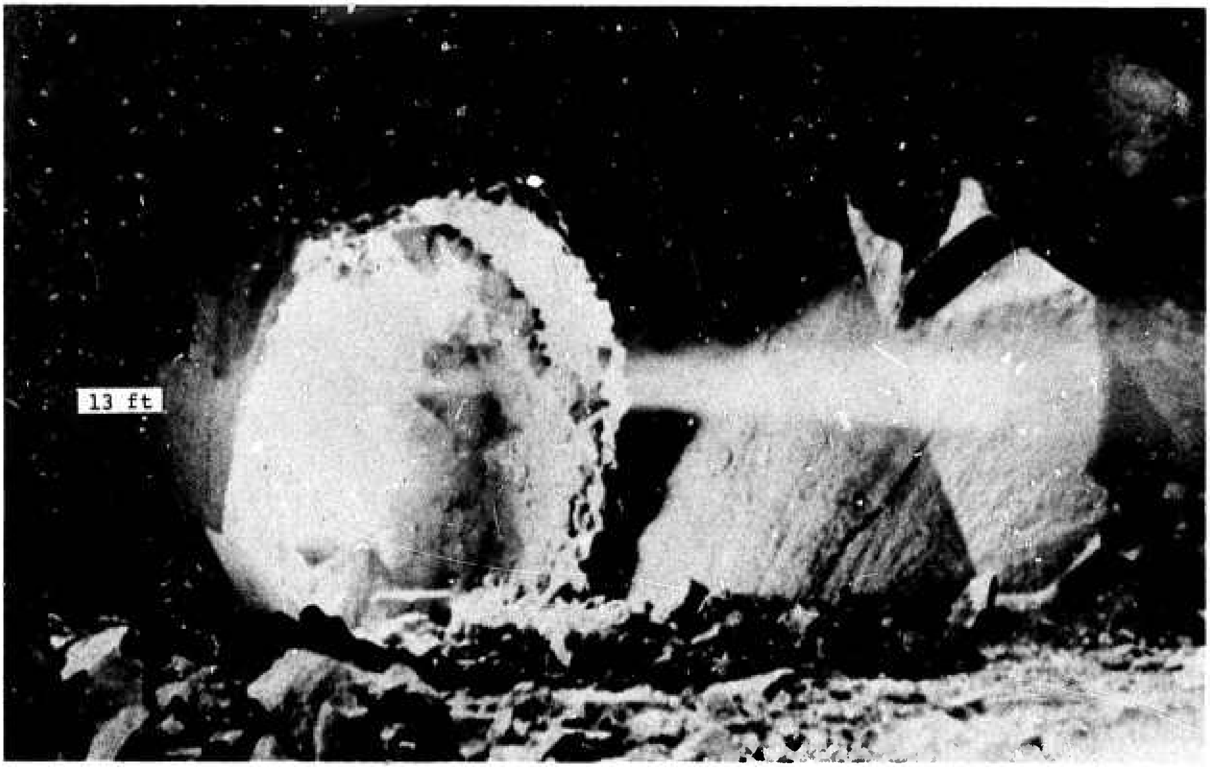

Figure 1 The fireball generated by a 10 pound concrete projectile impacting at 5000 ft/sec.

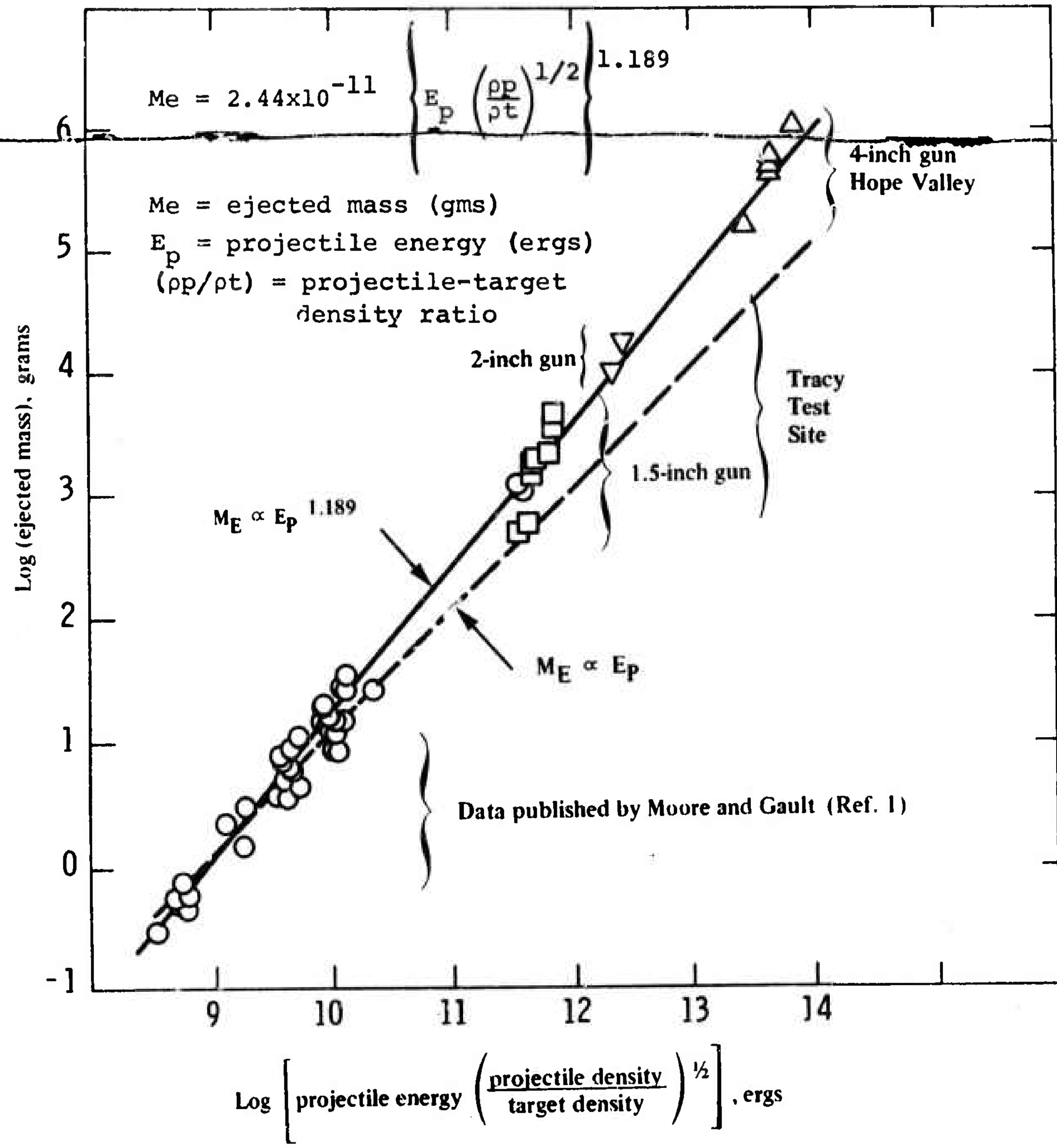

Figure 2 Experimental relationship between ejected mass and projectile impact energy. Solid line represents least squares fit to data published by Moore and Gault (Reference 1)

International's cratering data from 1.5-inch, 2-inch, and 4-inch guns firing into granite and granodiorite seem to confirm the scaling relation of Moore and Gault. The 4-inch gun data were obtained during this contract from the initial tunneling shots into the freshly developed granodiorite face at Hope Valley.

Using the Griffith theory of failure, where rupture strength is inversely proportional to the square root of defect size (Reference 1), it can be shown theoretically that mass ejected is proportional to impact energy raised to the power 1.2, ($M_e \propto E_p^{1.2}$) in agreement with experiment. The identical scaling relation has also been demonstrated by Hartman (Reference 3) as applying to percussive impact drill bits. Larger drill bits crater more efficiently because of the effectively reduced material strength with increasing scale.

While these results are for single impacts on a semi-infinite plane, our recent tunneling experiments demonstrated that, in a multiple impact situation, there is threefold increase in the average mass of rock ejected per shot because of the interactive effects between shots. The average mass of rock removed per shot while driving the tunnel was found to be 3000 pounds.

SECTION 2

FULL-SCALE FIELD TESTS OF THE REAM CONCEPT

The results of the field operations from the preparatory tests at Physics International's Tracy Test Site to the completion of tunneling at the Hope Valley Site are presented in this section. A more detailed account of the preparatory tests and site development is given in Reference 4.

2.1 PREPARATORY TESTS AND HARD ROCK TEST SITE DEVELOPMENT

The launcher used in the REAM field tests was a 105-mm smooth-bore gun loaned to Physics International by the U. S. Army Ballistic Research Laboratories at Aberdeen Proving Ground, Maryland. The gun is shown in Figure 3 on its self-propelled gun mount. Prior to moving to the hard-rock test site, the launcher underwent tests at Physics International's Tracy Test Site in California. Here, the operational characteristics of the gun were determined and several designs of concrete projectiles were tested.

2.1.1 Tracy Tests. Preliminary tests were carried out at the Tracy Test Site using the experimental arrangement shown in Figure 4. The purpose of testing several projectile configurations was to develop an inexpensive workable projectile to demonstrate the REAM concept for this initial contract. The designs tested and developed are in no way meant for large-scale

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a. 105 mm gun

b. 105 mm and 57 mm gun

Figure 3 The 105 mm and 57 mm guns loaned to Physics International by the Ballistic Research Laboratories for the REAM field tests.

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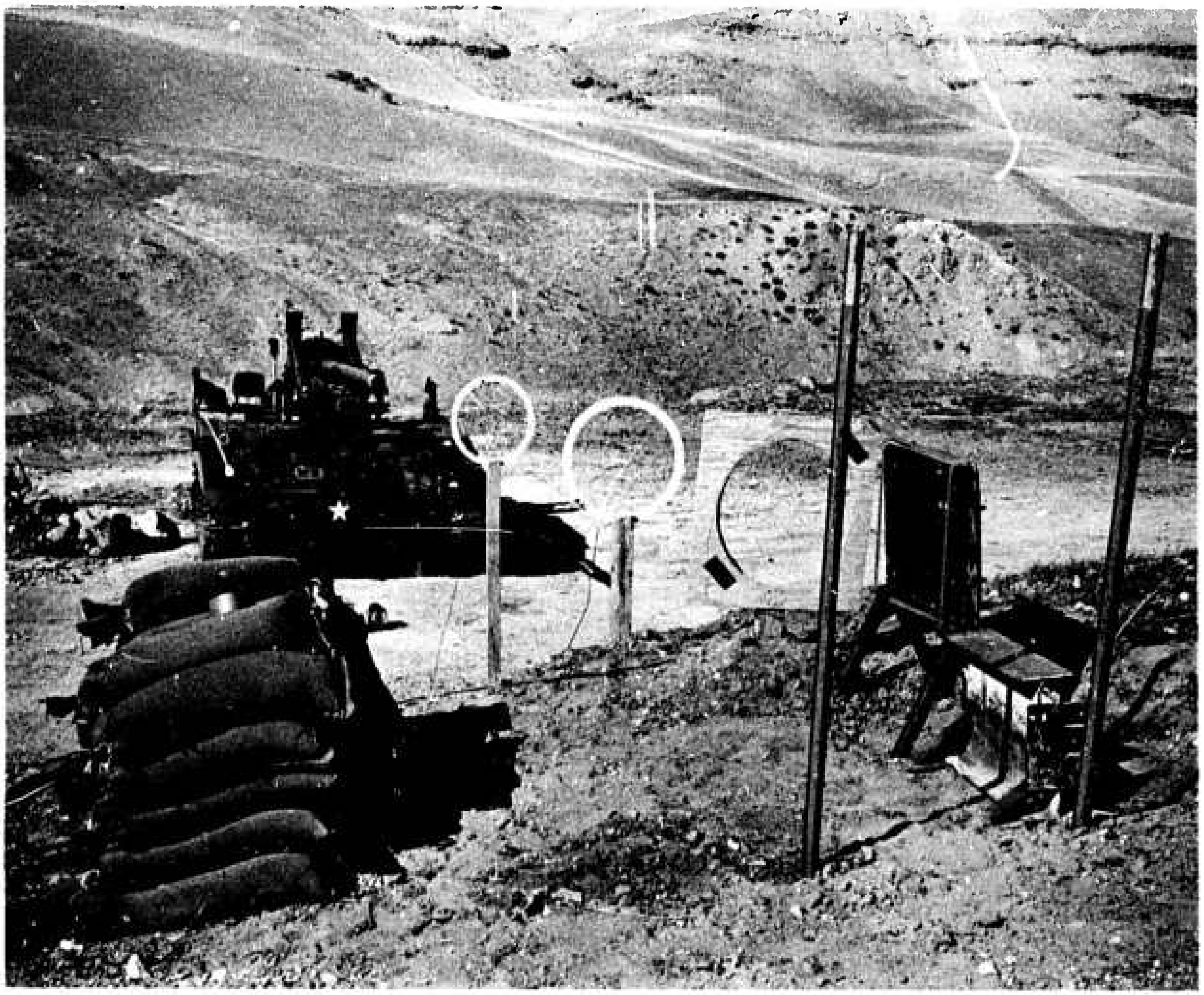


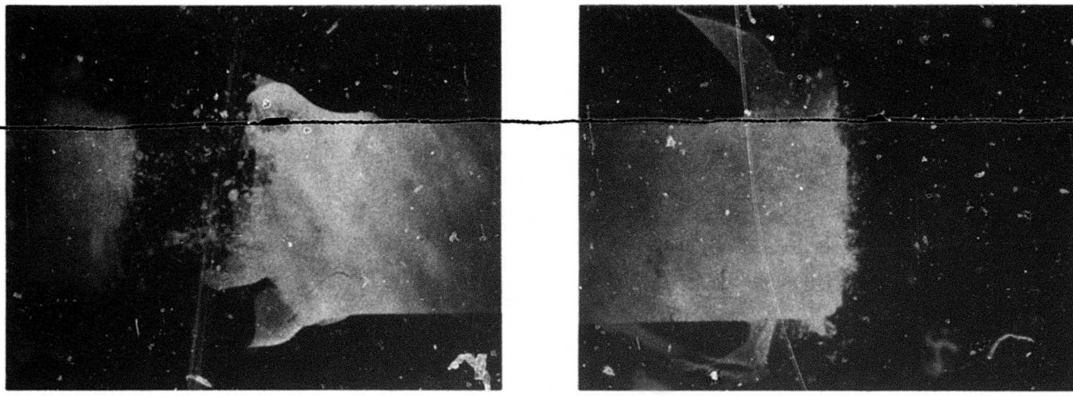
Figure 4 Tracy Test Site experiment to measure projectile velocity and to radiograph projectile condition during flight.

production. Most of the mass of the projectile was comprised of an ordinary concrete with iron filings added for increased density. The concrete mix was poured into a cylindrical sleeve, and during the test program cardboard, plastic, and aluminum sleeves were tested. A low-density polyethylene obturator (gas seal) was used in all designs to form the base of the projectile. Some of the configurations tested had front plates to protect the leading edge of the concrete from damage during flight.

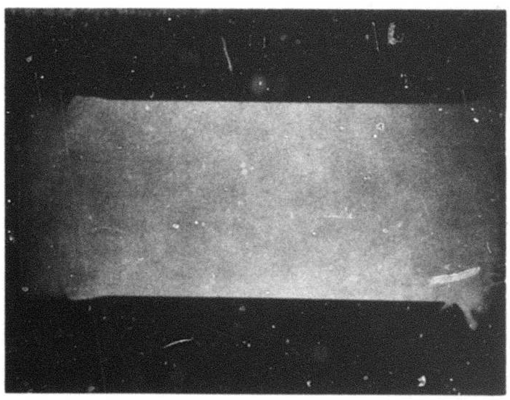
All of the designs tested were launched successfully; however, some of the projectiles without front plates and with improperly cured concrete exhibited severe frontal damage during flight, as shown in the pulsed radiographs of Figure 5.

The design selected for the field tests consisted, as shown in Figure 6, of a thin aluminum shell filled with concrete. The assembly had an aluminum front plate which was connected to the obturator by a long threaded rod. A cardboard sleeve was employed to match the outside diameter of the aluminum sleeve to the bore diameter of the launch tube. None of the tolerances in this design are considered critical. The particular advantage of this configuration was that no frontal damage occurs during flight even if the concrete is improperly cured. Figure 7 shows a pulsed radiograph of this projectile in flight. The concrete had been cured for less than 24 hours, and there is very little damage to the front after 40 feet of flight at 5500 ft/sec.

Tests with both concrete and steel projectiles showed that stable flight with no projectile breakup or appreciable tumbling was possible for distances of at least up to 300 feet. For any standoff distance less than 300 feet, the performance of the impacting projectiles should remain constant, with a small loss of effectiveness at the longer distances due to aerodynamic drag.

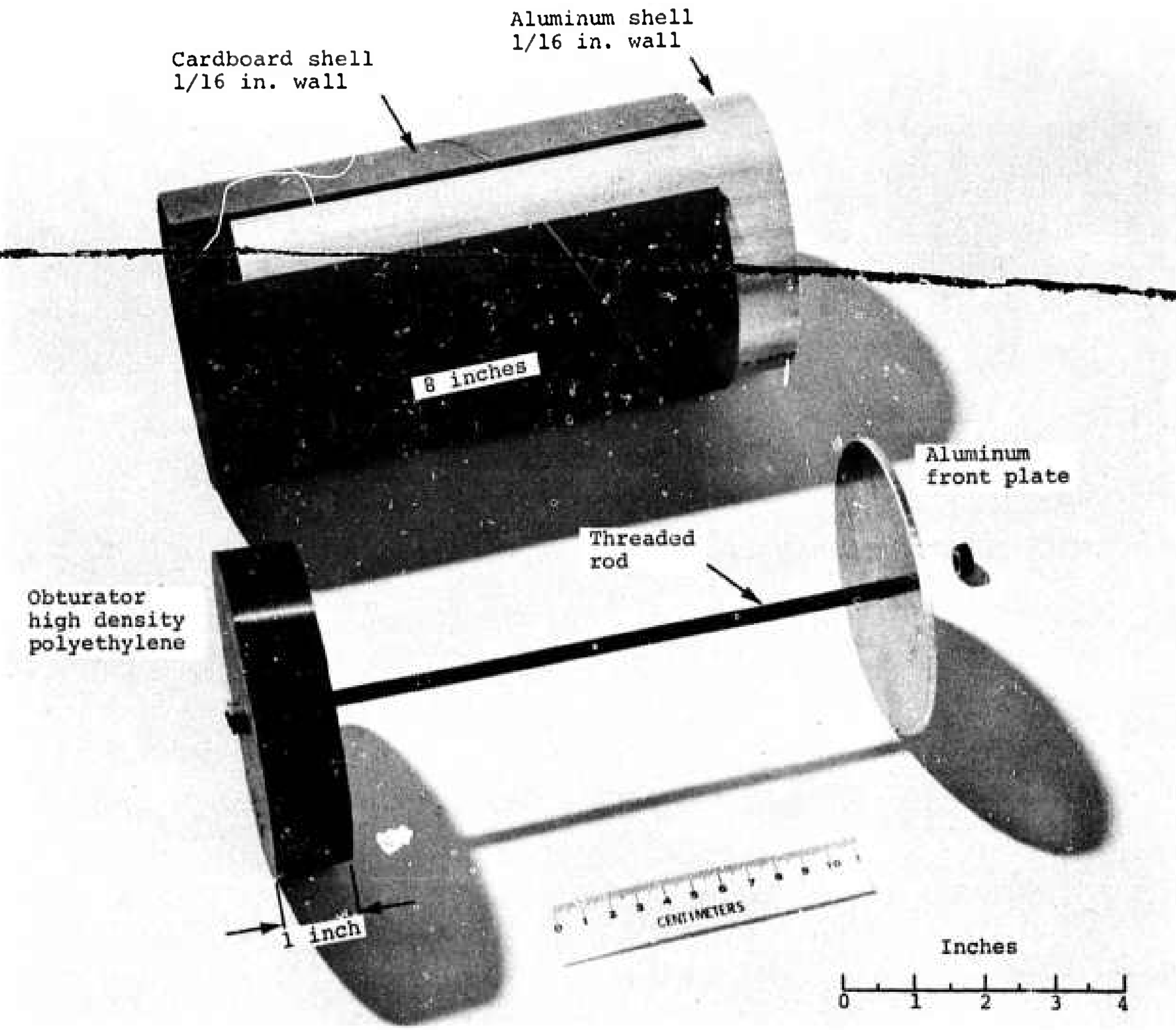


a. Concrete cure time of less than 2 days--no front plate



b. Plastic front-plate added and concrete cure time of 1 week.

Figure 5 Flash radiographs of early concrete projectile designs.



Gross weight 10 pounds
Concrete weight 8.5 pounds (density 156 lb/ft^3)
Cbturator weight 0.5 pounds

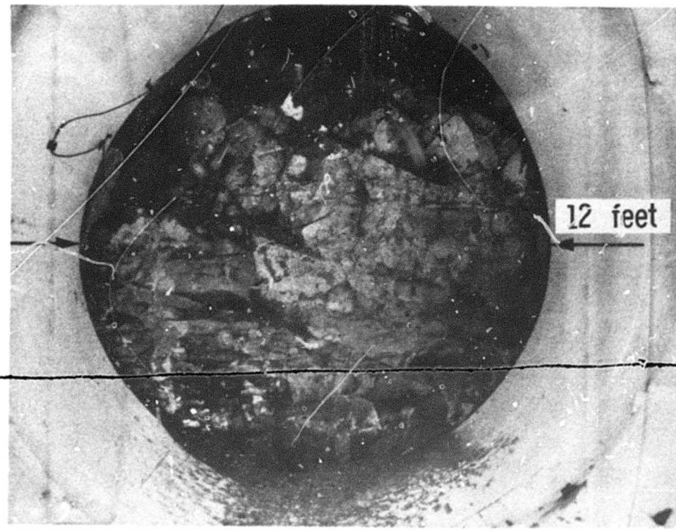
Figure 6 Construction of the final concrete projectile design--bolted assembly.

Figure 7 Flash radiograph of final concrete projectile design after flight of 40 feet at 5500 ft/sec.

During the Tracy tests, an experiment was conducted to attempt to muffle the noise associated with the muzzle blast of the gun. A 12-foot-diameter, 25-foot-long steel arch was positioned against a sandstone face. The arch was overburdened with earth. Heavy rubber mats were hung over the open end, and the muzzle of the gun was inserted. The results of the test demonstrated that a larger chamber would be required to effectively contain the muzzle blast.

One of the interesting sidelights of this experiment was that several tons of sandstone were dislodged by the impacting projectile (Figure 8). The compressive strength of the sandstone is estimated in the neighborhood of 1000 psi, but the result indicates that projectile impact may be quite effective in medium to soft rock--as long as there is a resonably brittle character to the rock.

2.1.2 Hard Rock Site Selection and Development. Concurrent with the Tracy tests, an exhaustive search was conducted for a suitable hardrock site for the REAM tests. Several quarries and remote sites in California and Nevada were investigated and most were found unsuitable either because of the quality of the rock, the close proximity of residential areas, or the time-consuming requirements of special permits. The location finally selected was on a private mining claim located in Hope Valley, California, just south of Lake Tahoe on the crest of the Sierra Nevada range. The rock present at the tunnel site was a medium-grained granodiorite of the Cretaceous age. The unconfined compressive yield strength determined from core samples taken from the formation is in the range of 20,000 to 25,000 psi. The major joint spacing of the formation is 6 to 8 feet.



a. Before

b. After

Figure 8 Ejected rock after one shot into a weak sandstone formation at the Tracy Test Site.

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After two weeks of mobilization of men and materials, the REAM project moved to Hope Valley. Initial efforts were directed toward improving the roads, receiving material, erecting buildings, and installing magazines for propellant and explosives. The site was equipped with a D-9 Caterpillar tractor, a Gardner-Denver air track, a back-hoe for mucking, several multi-axle trucks, and other support equipment.

Once the base of operations was established, development of the vertical rock face was begun. The area around the tunnel portal was cleared of underbrush and graded. Firetrails were bulldozed around the test area. The layout of the site after completion is shown schematically in Figure 9.

The vertical face was established by drilling and blasting approximately 40 feet beyond the original toe of the rock formation to expose a face of fresh granodiorite. During the preparation of the face, the launcher was used to bring down large blocks perched precariously on the formation (Figure 10). The gun was positioned about 200 feet from the face and was most convenient for bringing down inaccessible blocks, especially since it was not necessary to move the air track or D-9 completely out of the area as in drilling and blasting.

2.1.3 Secondary Breakage Experiments. Because of its convenience, the gun was also used to disintegrate several large boulders blasted out of the formation. Typically, one shot was required to fragment boulders weighing about 20 tons as shown in the sequence of Figure 11. One 40-ton boulder (Figure 12) required two shots; however, both shots impacted at a 30 degree angle to the normal line of impact and were good examples of difficult shots. One of the advantages of this method over that

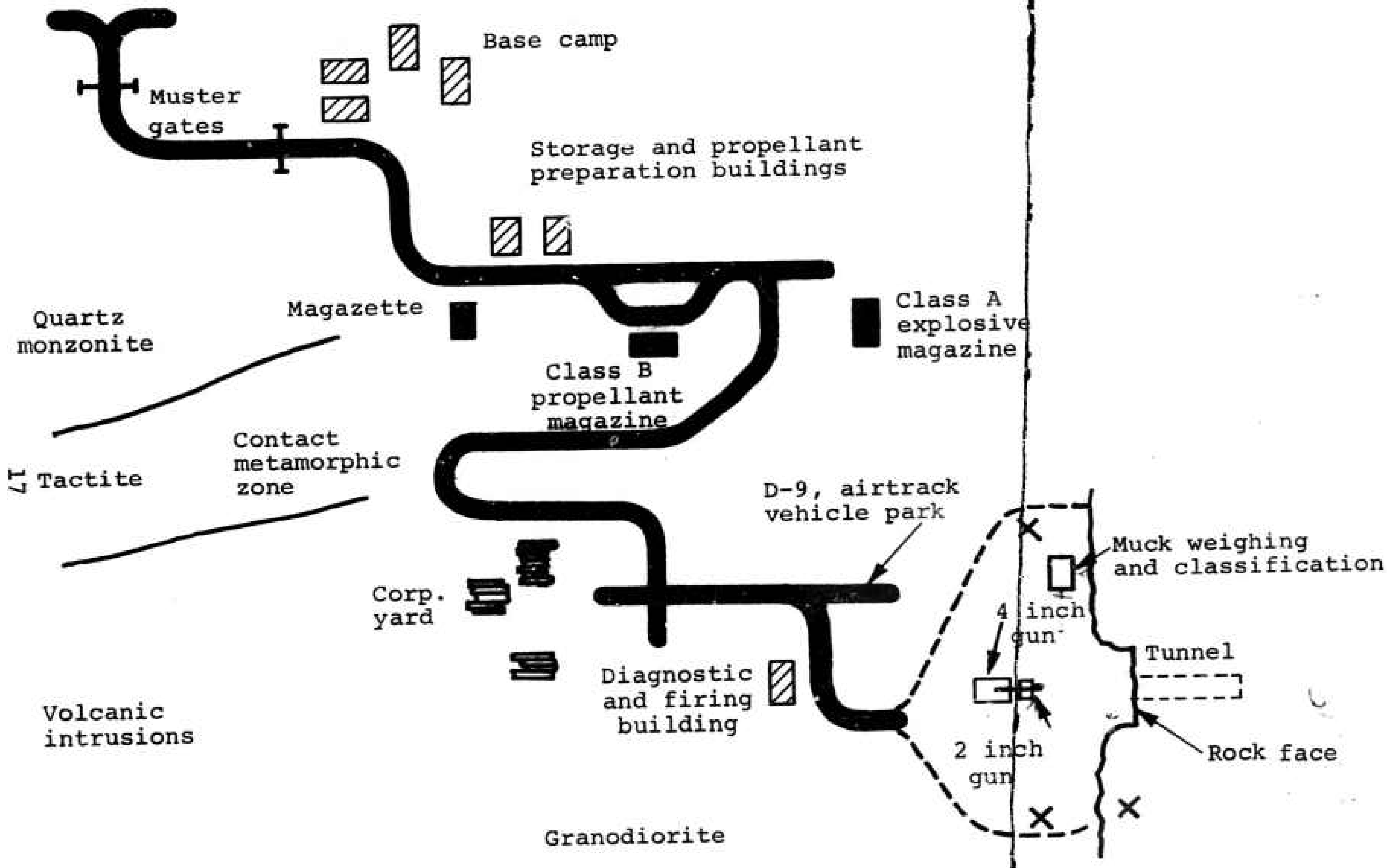
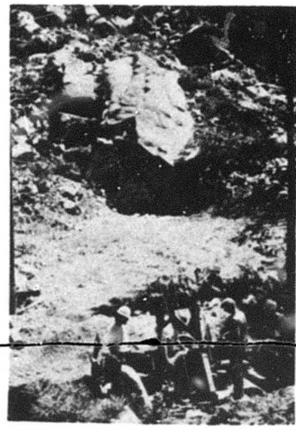


Figure 9 Layout of the Hope Valley Site.



a. Gun positioned for shooting

b. Before

c. After three shots

Figure 10 The REAM gun assisting in face development operation.

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a. Before impact

b. During impact

c. After impact

Figure 11 Large boulder disintegrated with one shot by the REAM gun.

a. Before; note 1 foot cross marking impact point

b. After impact

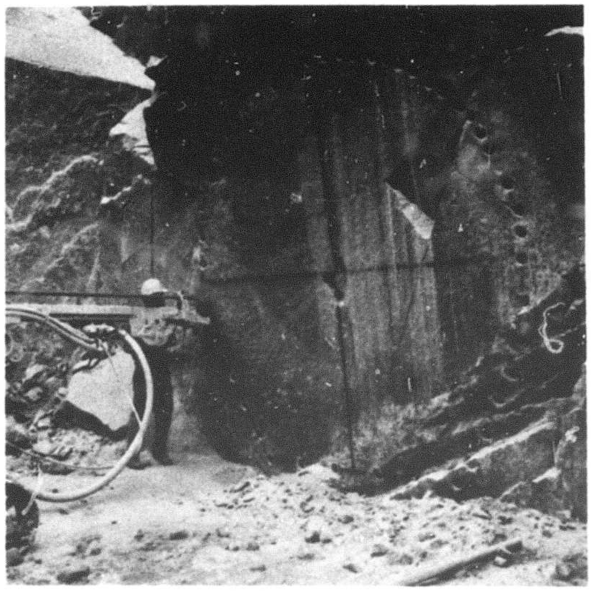
Figure 12 Large boulder disintegrated by two shots of the REAM gun. Both shots at 30 degree oblique angle to normal impact.

of mudcapping or blockholing is that there is very little throw and heavy equipment is not jeopardized by high-velocity fragments. Because heavy equipment need not be moved completely out of the vicinity, considerable time can be saved.

These tests suggested that a mobile launcher would be very effective in secondary breakage and other surface excavation operations. The average size of the problem boulders would dictate the bore size of the launch tube. For such applications, a relatively simple hand-loaded launcher with the necessary modifications for safety would be sufficient.

2.2 TUNNELING AT HOPE VALLEY

This section describes the results of the tunneling at the Hope Valley Site carried out during the summer and fall of 1972. After the vertical face was developed, the portal contour was outlined by line-drilling to a depth of 4 feet. The cross-sectional area of the horseshoe-shaped portal was equivalent to a 13-foot-diameter opening and the finished face is shown in Figure 13. Initial shots into the virgin face were used to obtain data for single craters in an effectively semi-infinite plane. These results were discussed earlier and are shown in Figure 2. After ten shots were fired, the entire face collapsed, although it was evident after three or four shots that the major blocks forming the face were shifting. Apparently the local formation had been disturbed by the previous drilling and blasting operations for face preparation.



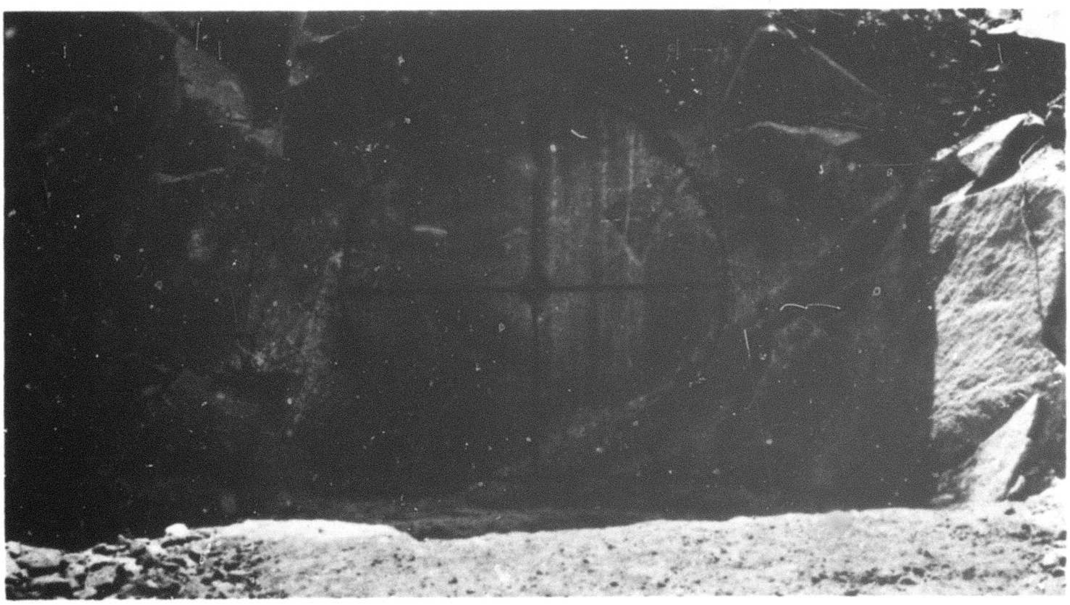


Figure 13 The vertical rock face prior to the start of tunneling.

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The rubble was cleared away by the gun acting in concert with the D-9 tractor and a new, more massive vertical face was exposed. Again the portal contour was line-drilled, this time to a depth of 20 feet. The line-drilling consisted of 3-inch holes on 8-inch centers. This time, however, the floor of the tunnel was not line-drilled. During subsequent tunneling operations, the vertical face remained solid, exhibiting no perceptible motion. After tunneling into a depth of 12 feet, the vertical face was rock bolted as a safety precaution and in compliance with the Industrial Safety Board of California.

2.2.1 Performance of the REAM Launcher for Rock Disintegration. Once the second vertical face was established, tunneling was resumed with the 4.2-inch gun positioned about 50 feet from the face (Figure 14). Initial shots again provided data for single craters in an effectively semi-infinite plane. For the first four or six shots into the face, the average breakage was about 1000 pounds of rock per shot. After these shots had conditioned the rock, however, the average breakage per shot increased to about 3000 pounds and remained at this level for the duration of tunneling. This represents a substantial increase over the 1000 pounds broken out by a single crater in a semi-infinite face and is due to the interactive effects between successive impacts. The magnitude of the interactive effects represents the major finding of the Hope Valley tunnel experiments.

The typical firing pattern employed during tunneling is shown in Figure 15. First the bottom was undercut by four shots placed about a foot above the floor. This resulted in an undercut depth of about 11 to 13 inches and an overbreak into the floor of 3 to 4 inches.

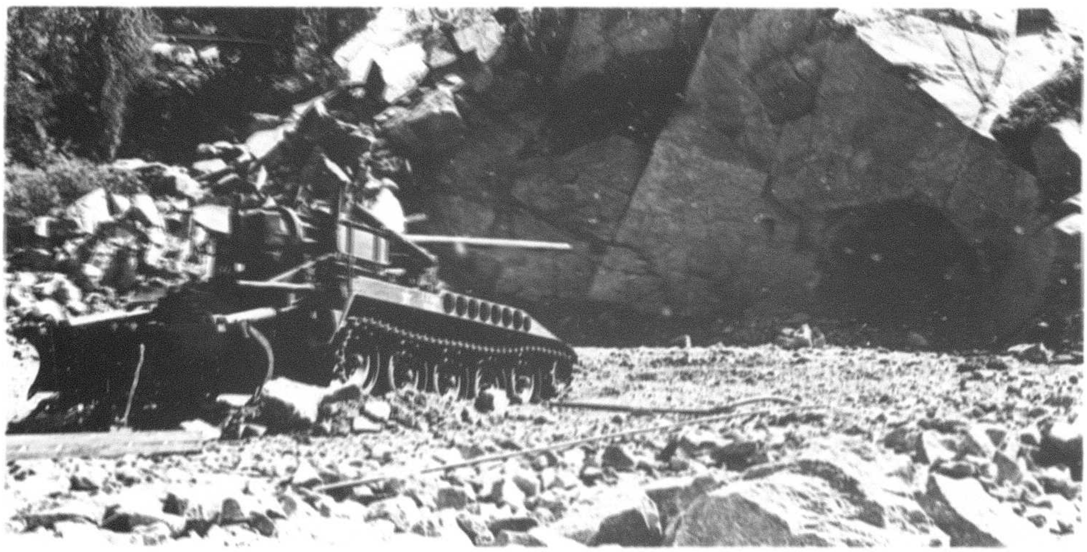

Figure 14 The 105 mm gun on mobile mount in firing position for tunneling.

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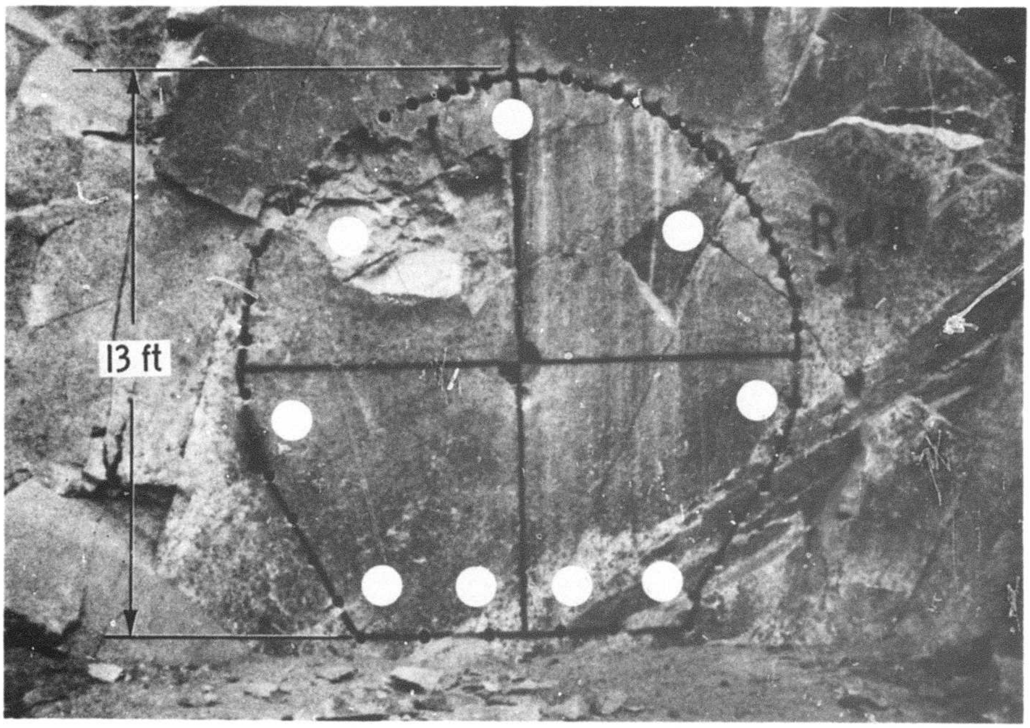

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Figure 15 Typical pattern of shots for advancing the face (13-ft height); bottom shots are fired first.

After the bottom shots were fired, providing a free surface for the upper shots, shooting would proceed around the periphery, 15 to 18 inches from the wall, in a pattern of five shots, as shown in Figure 15. The center portion of the tunnel would fall out of its own accord as it became undercut and laced by fractures from successive impacts. A variation of this pattern commonly employed was to fire a double row of bottom shots and then a double sequence of periphery shots.

Two hundred and five shots were required to drive 26 feet of tunnel, and the average advance rate of 8 shots per foot was quite consistent over the entire length. The nearly completed tunnel is shown in Figures 16 and 17 and the depth of the tunnel at various stages is illustrated schematically in Figure 18.

Most of the shots were fired into rock fractured by previous impacts and the impacts were often as much as 20 to 30 degrees off normal, but these seemed to have little effect on the average breakage. It was consistently observed that the amount of rock broken in the bottom shots was considerably less than that of the upper shots; the upper shots, of course, always had an extra free surface provided by the undercutting bottom shots.

The walls of the first 20 feet of tunnel were line-drilled while the last 6 feet of tunnel were driven into undisturbed rock. The average breakage per shot appeared to be independent of whether the contour was line-drilled or not. The main effect of the line-drilling appeared to be in controlling overbreak. This is discussed more fully in the following subsection.

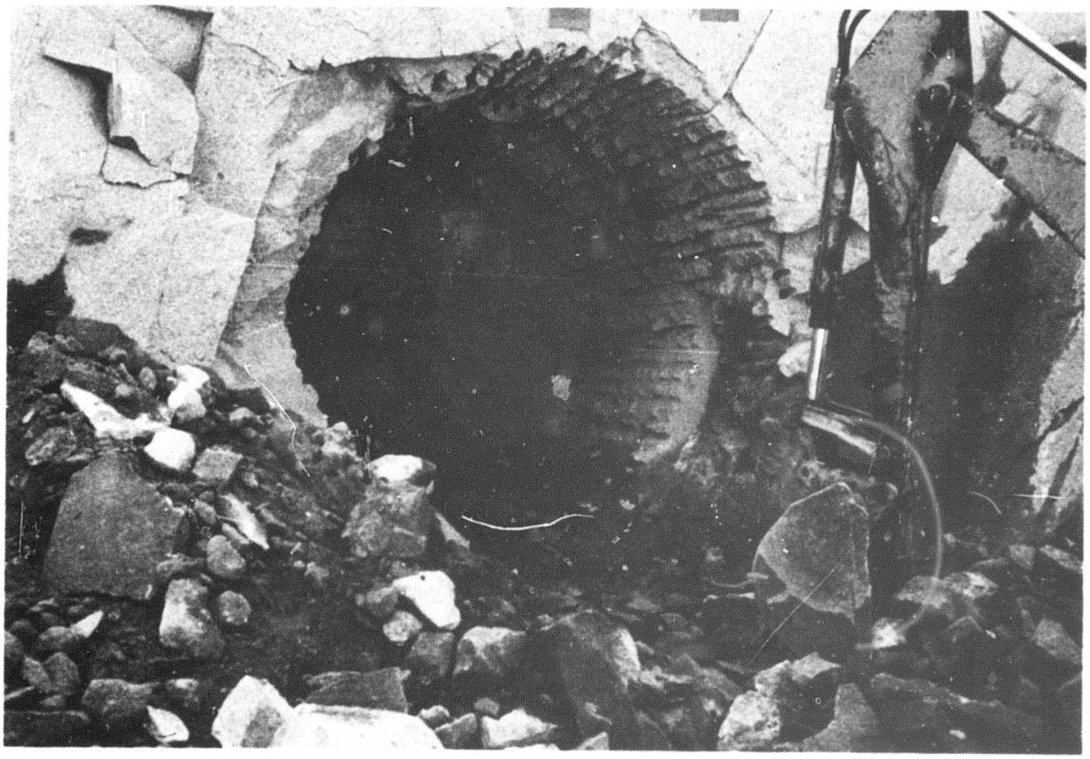

Figure 16 The Hope Valley tunnel near completion--tunnel depth is about 22 feet.

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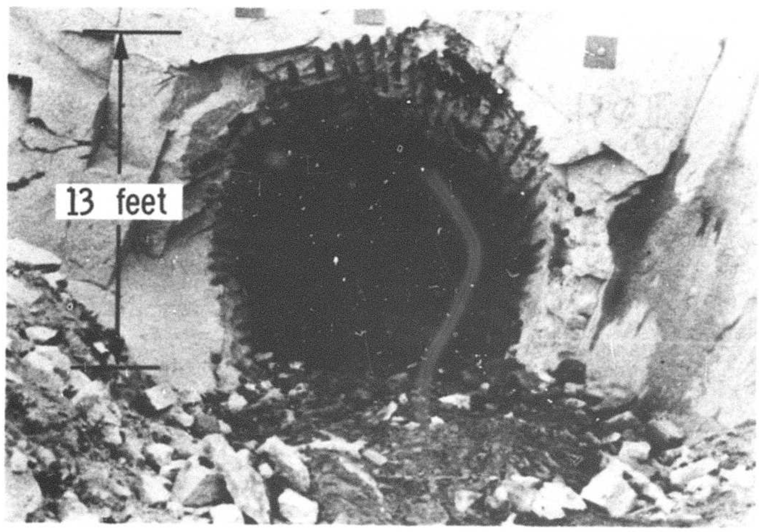


Figure 17 The tunnel near completion; tunnel depth is about 24 feet.

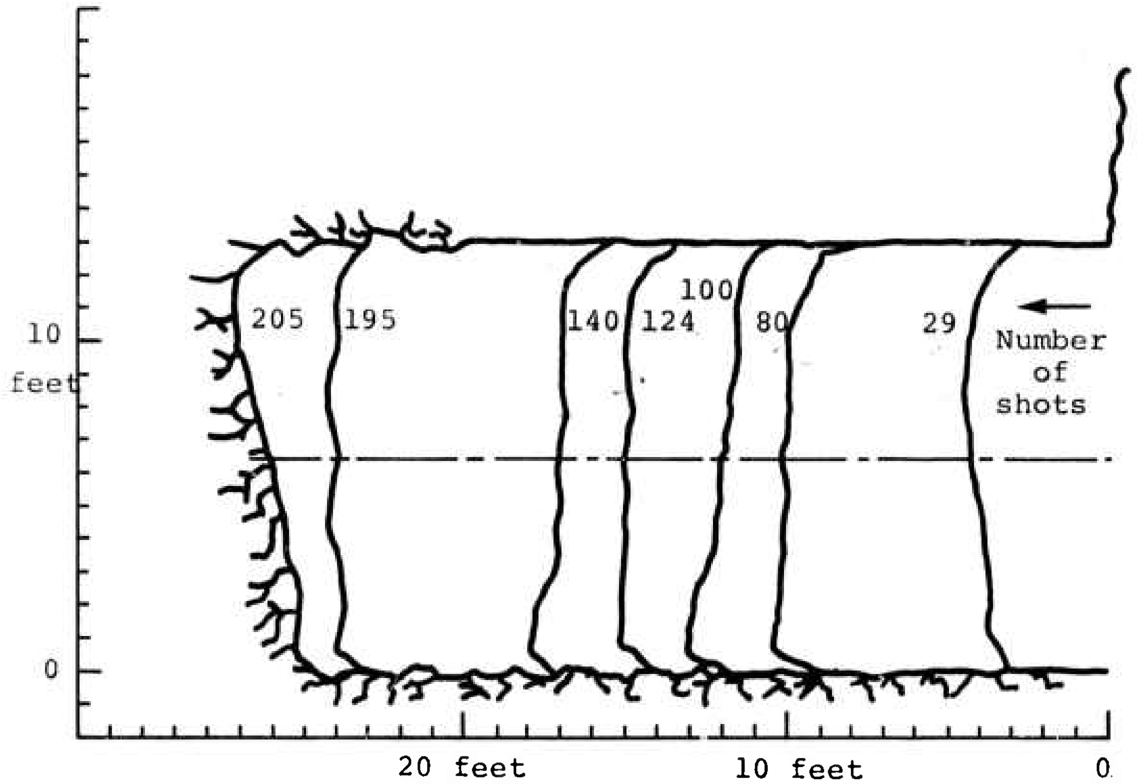
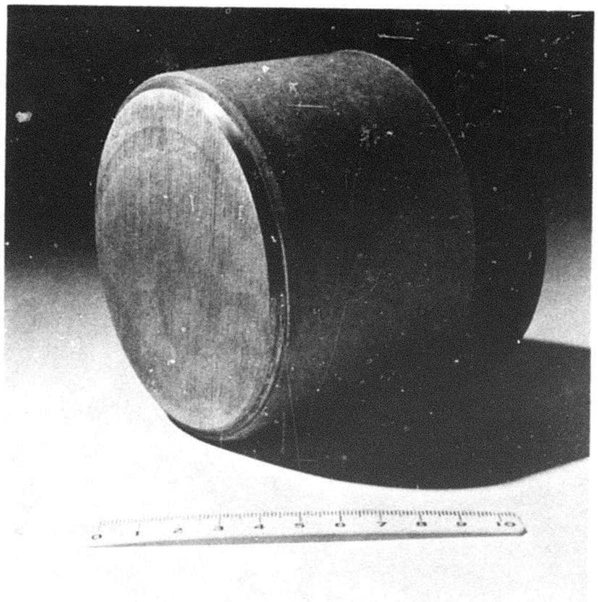


Figure 18 Tunnel depth at various stages of shooting--depths taken along the vertical centerline.

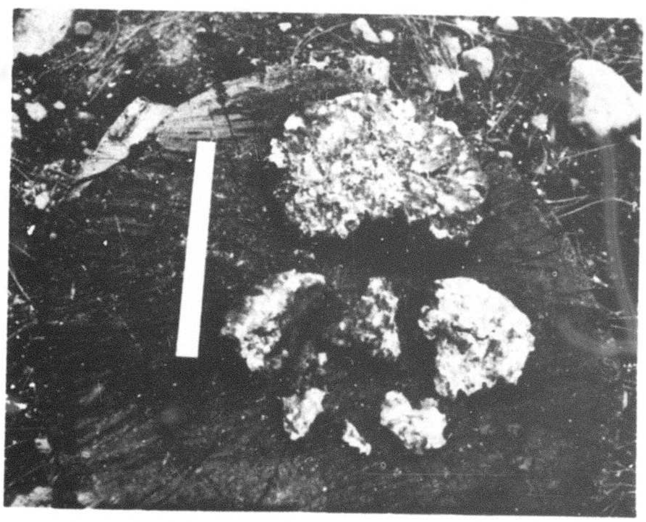
Twelve shots were fired using 10 pound steel projectiles rather than concrete. This was not enough data to determine if the steel projectiles were more effective than the concrete, although qualitative observations indicate that they may well be. For single-impact craters in a semi-infinite plane, a steel projectile of the same mass and velocity will remove over twice the mass of rock as a concrete projectile. This is because of the increased density of the projectile and has been shown experimentally (Reference 1). However, the energy and momentum of impact are the same for both projectiles, and, in a tunneling situation where the breakage is dominated by the interaction of successive impacts, it is probable that steel projectiles are not much more effective than concrete.

In these tests, mild steel projectiles were used, and there appeared to be a hazard from large rebounding fragments (Figure 19) when the projectiles impacted normally on a solid surface. However, if tempered steel were used, it is felt that the stronger but more brittle steel would completely fragment upon impact. This was observed in one experiment at the Tracy Test Site early in the program when a heat-treated alloy steel projectile was fired at a Raymond granite block (Reference 4). Both the 5-1/2 ton granite block and the steel projectile were completely disintegrated.

The cross-sectional area of the tunnel increased slightly with depth because of divergence of the line-drilling holes. Taking this into account, the average breakage per shot was almost exactly 3000 pounds. Since the nominal projectile impact velocity was 5000 ft/sec and the nominal impact mass was 10 pounds, the energy of impact is 3.9 million foot-pounds, and the average specific energy for rock removal is 120 ft-lb/in.^{3}.



a. Before, showing cardboard sleeve and plastic obturator.



b. After, shown with 12 inch rule

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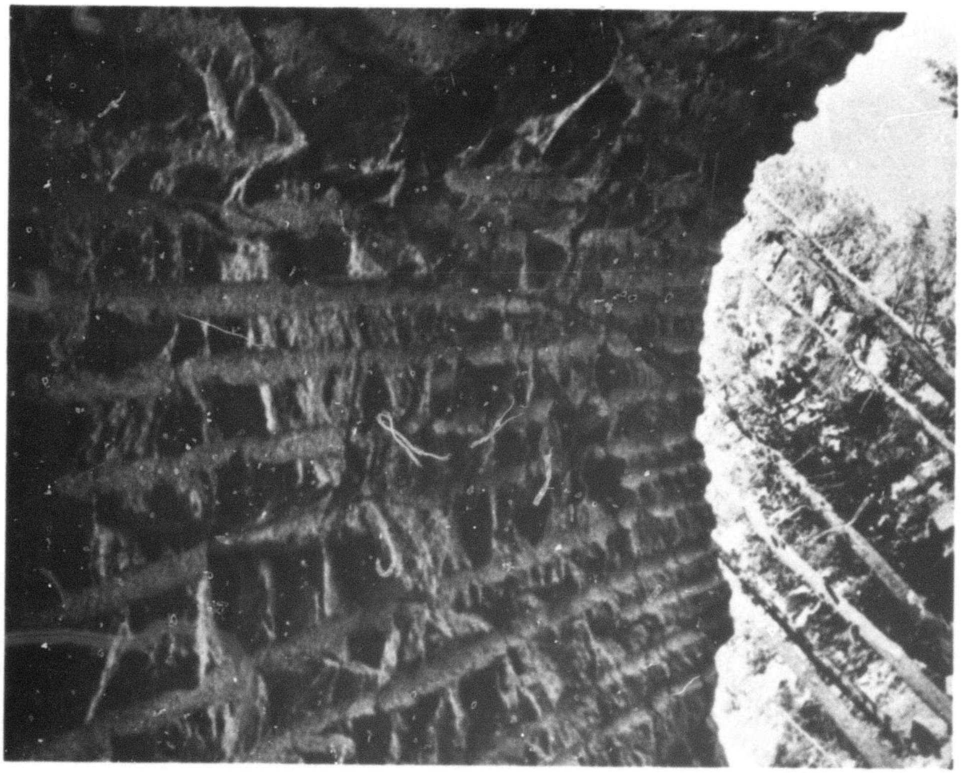
Figure 19 Ten-pound mild steel projectile before and after impact into granite. Tempered steel projectiles tend to break into small fragments such as the smallest one shown.

Considering that with modern gun technology projectiles can be accelerated to 5500 ft/sec with propellant-to-projectile-mass ratios of unity, the method of projectile impact would require about 10 pounds of propellant to remove 3000 pounds in 25,000-psi granitic rock.

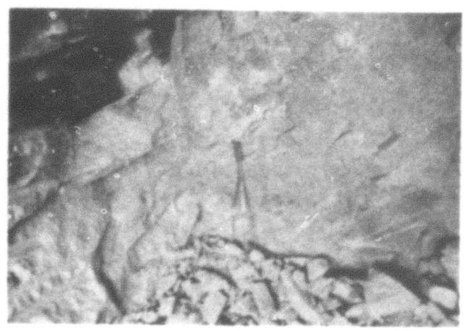
2.2.2 Contour Control and Overbreak. For safety reasons, the wall contour of the first 20 feet of tunnel was line-drilled by 3-inch holes on 8-inch centers. The floor, however, was not line-drilled. As shown in Figure 20, the walls of the first 20 feet of tunnel were exceptionally smooth with virtually no overbreak. The walls in this portion of the tunnel were quite solid even in the vicinity of major joints.

After the tunnel was roughed out, there were protrusions on the walls. These were trimmed by using a 57-mm smooth-bore gun which fired 1-1/4-pound concrete or aluminum projectiles at about 4900 ft/sec. This gun (shown in Figure 3) was positioned under the muzzle of the larger gun and was very effective for trimming the walls and could remove anywhere up to several hundred pounds of rock per shot, depending on the circumstances. Several shots from this smaller gun were used to develop an impact face for the larger gun in particularly difficult situations. For example, a major joint ran nearly parallel to the tunnel angling in from the right wall (Figure 21). Rather than use the large gun inefficiently, five shots of the smaller gun were used to develop a flat on the leading edge of the rock and one shot from the large gun eliminated most of the remainder of the rock intrusion (Figure 21).



a. The walls in the line-drilled section near the portal

b. Walls in the line-drilled section



c. End of the tunnel and walls trimmed with the 57 mm gun

Figure 20 The finished tunnel walls.

a. The oblique face is developing into a problem

b. **Flat surface is formed using 5 shots with the 57 mm gun**

c. One shot with the 105 mm gun removes most of the obstruction

Figure 21 Elimination of an oblique face using the 57 mm gun to establish an impact point for the 105 mm gun.

A2544

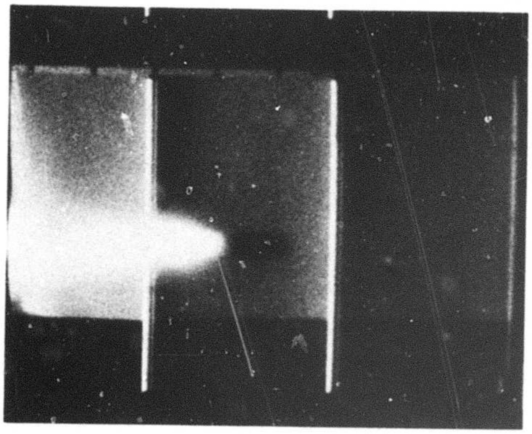
The 57-mm gun was also used to remove protrusions in the floor. As indicated before, the bottom shots from the large gun, overbroke the floor to a depth of 3 or 4 inches. Occasionally, however, there were protrusions and these were effectively removed with one or two shots from the small gun. On the average, two shots of the trimming gun were required per foot of tunnel in the line-drilled section.

The 57-mm gun was used to control the contour in the last six feet of tunnel, which was blasted out of undisturbed rock and again proved quite effective. In this section of the tunnel (Figure 20)--where there was no line-drilling--the overbreak could be as much as 12 inches, but this was dictated more by the jointing in the rock than by the lateral damage from the impacting projectiles. The rock at the heading appeared to be broken to a depth of 12 to 18 inches by the continual impacting. However, the damage to the rock in the lateral direction was observed to be much less severe. This is because the momentum of the projectile directs most of the energy along the line of flight.

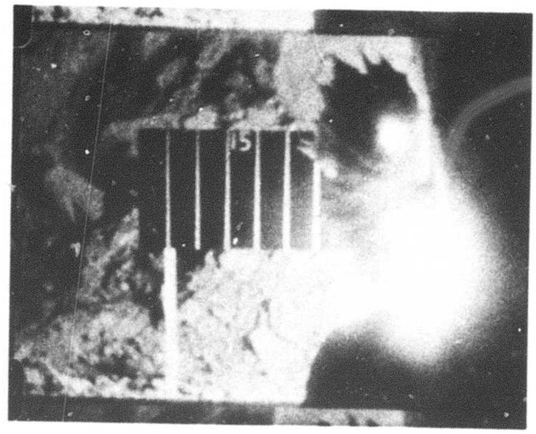
It is concluded that line-drilling represents an effective method of smooth wall tunneling in conjunction with the REAM method, although no attempt was made to optimize the size or number of holes required. In the 6 feet of tunnel driven without pre-kerfing, it appears that the REAM gun, assisted by smaller trimming guns, can tunnel without excessive overbreak. Based on the ease with which the floor of the tunnel and the walls of the last 6 feet of tunnel were formed using guns only, it is felt that no method of pre-kerfing is necessary for the REAM concept to be effective in most mining and tunneling applications. It is recommended, however, that another 20 or 30 feet of tunnel be driven with guns to confirm this preliminary observation.

2.2.3 Ejecta and Muck Characteristics. One of the objectives of the Hope Valley tunneling experiments was to provide initial data on the hazard of high-speed ejecta particles from the impact. Using high-speed cameras, the velocity and deceleration of the leading edge of the ejecta were measured. Figure 22 shows the ejecta in the initial stages after impact of a 10-pound concrete projectile at 5000 ft/sec. It was found that the size of particles in the leading edge was very small--on the order of a few millimeters or less--and that the velocity of the leading edge decays very rapidly from about 5000 ft/sec to a few hundred feet per second after approximately 40 feet. The gun, mounted on a tracked vehicle, was 50 feet from the face and there was a recording camera beside the gun. In over 200 shots, there was only minor surface damage to the gun mount and no damage to the camera. Larger pieces of ejecta weighing several grams were occasionally found up to 80 feet from the face but their ejecta velocity must have been very low--less than 150 ft/sec. In general, it was observed that there was very little hazard from ejecta when concrete projectiles were used. However, when steel projectiles were used, it was found that small projectile fragments could cause pitting on the gun mount.

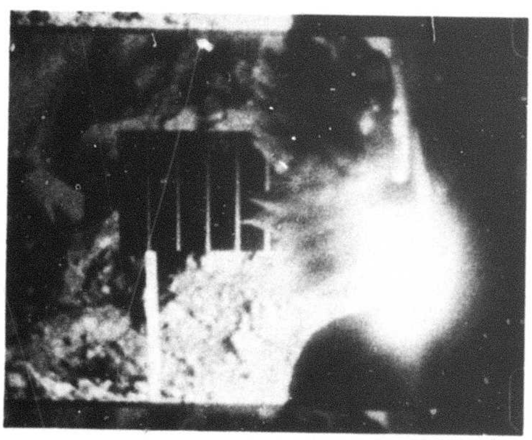
Because of time limitations, it was not possible to carry out as planned a detailed measurement of the space and size distribution of the muck. However, many observations were made that suggest that the distribution of muck is quite favorable for remote mucking operations in an underground setting. As indicated above, small fragments up to several grams were ejected a considerable distance. This represented a very small fraction by weight of the total debris.



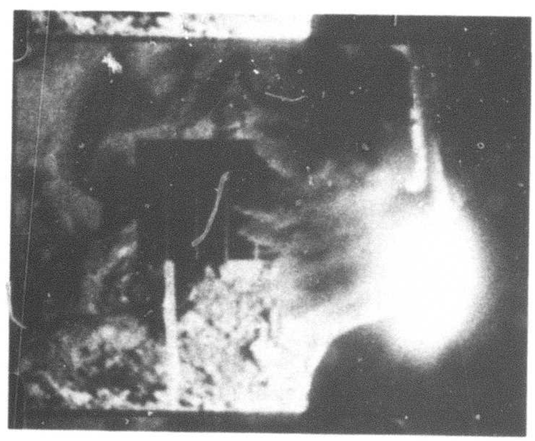
a. 10 lb concrete projectile at 5500 ft/sec--grid lines are at 3 foot intervals



b. 1 msec after impact--grid lines are at 1 foot intervals



c. 1.5 msec after impact



d. 2 msec after impact

Figure 22 Sequence of high-speed photographs showing the leading edge of the ejecta just after projectile impact.

Most of the muck produced by the impacting projectiles was found within 20 feet of the face. Figure 23 shows a typical distribution of muck after seven or eight shots. The major fraction of muck, estimated at about 80 percent, consisted of pieces of less than 30 pounds. Occasionally larger pieces--up to 150 pounds--would be dislodged from the center of the tunnel, but the procedure here was to fragment the larger pieces by shooting at them with our 57 mm gun. Examples of muck piles produced during the tunneling at Hope Valley are shown in Figure 24. The ejected rock usually had sufficient energy to fall 2 or 3 feet away from the face. Since we usually undercut the bottom, it would seem that a low-profile mucking machine that could crowd the bottom would be effective for collecting the broken rock.

The shots fired during the dry summer months raised a lot of dust, most of it being entrained by the muzzle blast as it swept along the ground. At the end of the program, several shots were fired in a drizzling rain. With the ground wetted down, it was observed that there was very little dust after shooting. These shots suggested that a simple water spray-down system in combination with a good ventilation system would be effective in controlling dust during underground operation.

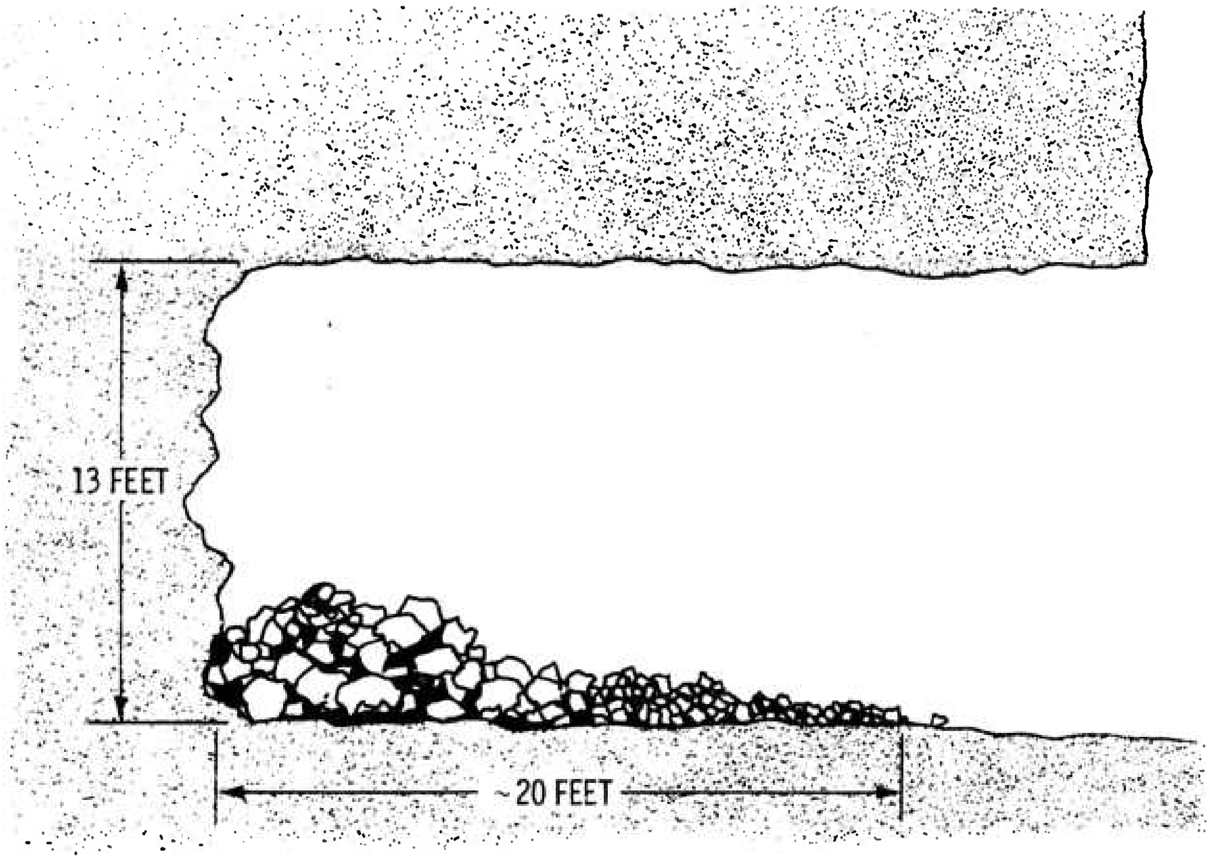


Figure 23 Schematic of typical muck distribution with a throw of 20 feet after 7 or 8 shots.

a. Typical muck pile after removal from tunnel; note occasional large boulder

b. Note geologist's hammer

c. Muck pile after about 20 shots

Figure 24 Typical muck piles.

SECTION 3
APPLICATION OF THE FIELD TEST RESULTS

In this section, the results of the Hope Valley tunneling experiments are used to develop a conceptual system for high-speed tunneling. The economics of such a high-speed tunneling system are discussed and compared to those of conventional drill and blast. One of the key elements in any REAM system is the development of a launcher that uses safe and inexpensive propellants. A brief discussion of current launcher and propellant technology is presented.

It should be noted that while this section concentrates on high-speed tunneling, there is application of the REAM concept to many mining and surface excavation operations. In the Hope Valley experiments, it was demonstrated that projectile impact could effectively break hard rock in both surface and subsurface settings. The conceptual system described below indicates that the concept is flexible enough to be used for remote excavation of adits of variable size and shape; its application to mining operations is easily seen. However, consideration of the economics of mining and surface excavations is beyond the scope of this contract. Sufficient to say that the REAM technique would be competitive in nearly all types of excavation operations when propellants costing less than 10 cents a pound are available.

3.1 CONCEPTUAL HIGH-SPEED TUNNELING SYSTEM

Figure 25 shows a conceptual system utilizing projectile impact for a high-speed tunneling project. The system shown consists of three major elements: a launcher assembly, a mucking device, and an acoustic baffle which isolates the working area. The system is directed remotely from behind the baffle and no personnel are required in the working area. For simplicity, no ground support apparatus is shown although there is space for additional equipment near the face.

The launcher assembly shown as a four barrel device is positioned approximately 50 feet from the working face, although there is no particular standoff requirement. Included on the assembly are several smaller trimming guns for removing wall protrusions and disintegrating large rocks in the muck pile. The launcher would be remotely operated and would use a liquid propellant which is stored behind the baffle in a safe location and pumped into the guns when required. Each of the guns would be capable of firing one shot per minute--a rate well within present technology. The barrels or launch tubes would be smooth bore and, using the liquid propellants, would have a useful lifetime of several thousand rounds. Barrels or barrel inserts would be replaced in minutes at a convenient time, presumably between shifts.

The mucking device would be a low-profile machine that operates independent of the launcher. The one shown in concept crowds the bottom of the face, catches the ejected rock, and transports it by means of conveyors under the launcher and through the acoustic baffle to the materials handling system. The mucking device might include a telescoping scoop for scaling and

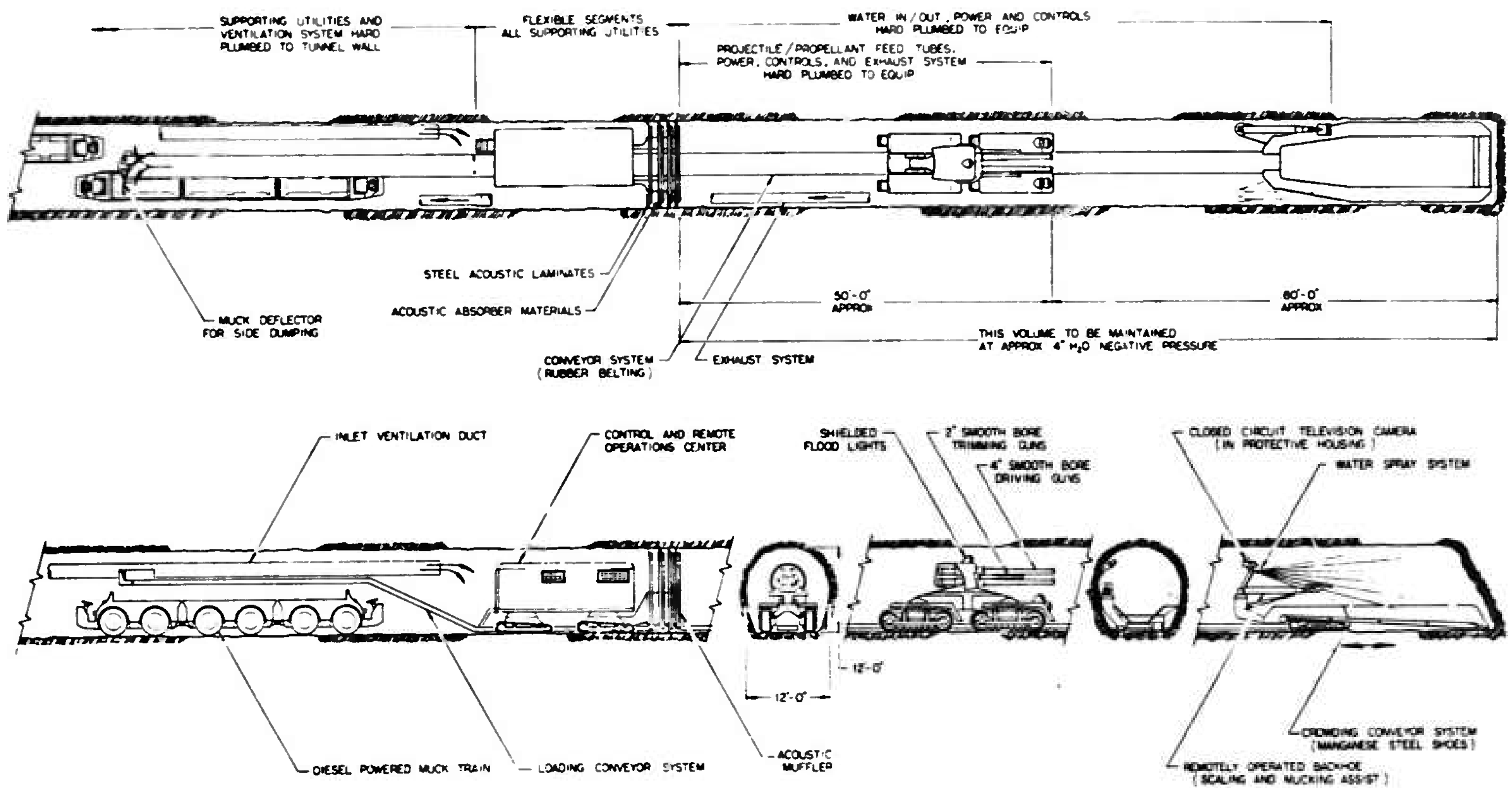


Figure 25 A conceptual high-speed tunneling system based on the results of the field tests at Hope Valley.

barring down operations and for removing rock wedged in the toe. The mucking machine would presumably not be moved while the gun is firing since there is little hazard to it from high-speed ejecta.

The acoustic baffle, positioned about 40 feet behind the gun, would isolate the heading and contain all dust, noise, and propellant gases. The baffle would be a heavy structure that would act as a plug and would probably be a sandwich of steel plates and acoustic material. The muck conveyors would pass through a door in the baffle which could be closed during the moment of firing.

A water spray-down system would be incorporated to provide a fine mist in the area behind the launcher and in certain areas ahead of the launcher. The water spray system would be activated just prior to firing and would serve a dual purpose. First, the spray would act as an energy absorber and greatly reduce the pressure rise from the muzzle blast. Second, the spray would wet down the walls and floor and suppress the dust.

A conventional large-capacity ventilation system would be used to rapidly remove toxic products (approximately 10 pounds of combustion products generated per minute in a 10-foot-diameter tunnel). The operation would be directed remotely from a control room behind the acoustic baffle, using several closed-circuit TV cameras located in the working area.

3.2 COSTS OF HIGH-SPEED TUNNELING WITH REAM

Based on the conceptual system described above and on the results of the Hope Valley experiments, Jacobs Associates of San Francisco carried out an analysis of the performance and cost of REAM in a high-speed tunneling operation and compared the results with those estimated using drill and blast. Their analysis (reproduced in its entirety in Appendix A) assumed no ground support requirements, some overbreak, rail haulage, and no unusual delays.

Jacobs Associates considered three cases: (1) A 10-foot-diameter tunnel using 4-inch guns, (2) a 20-foot-diameter tunnel using 4-inch guns, and (3) a 20-foot-diameter tunnel using 8-inch guns. The conclusions of their analysis showed that advance rates of 226 ft/day in case 1, and 550 ft/day in case 3 are practical for costs estimated to be about 60 percent those of conventional drill and blast. Their analysis also showed that advance rates are limited by the ability of the materials handling system to remove the excavated rock from the tunnel. For example, in the 10-foot-diameter tunnel, the firing rate for the launcher assembly is about one shot per minute. For a four barrel device this corresponds to a shot every 4 minutes for each barrel.

There appears to be substantial room for cost reduction by improving the method of materials handling and allowing higher advance rates for the same crew size.

While the above discussion is directed towards high-speed tunneling applications, the REAM method does have several advantages for mining situations. It is a flexible system that can drive shafts of varying size and cross sections. Sharp corners can be formed by removing a short section of the barrel and operating the guns a little less efficiently. The system should be economical for a variety of mining situations if propellants costing less than 10 cents/pound are utilized; (the Jacobs study was based on propellant costs of 21 cents/pound).

3.3 LAUNCHER REQUIREMENTS FOR THE REAM SYSTEM

One of the major advantages of the REAM method is that it utilizes existing technology. Therefore, it should be expected that very little development would be required to bring a practical system to fruition. It is presently possible to use solid propellants with a propellant-to-projectile-mass ratio of unity to launch 10-pound projectiles to over 5000 ft/sec. However, the cost per round of the powder and propellant case would render marginal the economics of REAM in a high-speed tunneling situation, although very high advance rates could prove decisive in certain situations.

At this time, liquid propellants appear to offer the most attractive approach to a truly cost effective REAM system. Liquid propellants have several major advantages. There are many combinations available, several of which have excellent handling characteristics and are low-cost, relatively abundant chemicals (such as hydroxyl ammonium nitrate). Being liquids, they can be stored, pumped, and injected by conventional hydraulic systems. These propellants can be easily metered into the combustion chamber, thus opening the possibility of varying projectile mass or velocity with the same gun. Liquid propellants are capable of high performance because of the unique manner in which combustion occurs. Velocities up to 8000 ft/sec have been achieved. One very major advantage of liquid propellants is that barrel wear is substantially reduced because of a liquid coating in the barrel during projectile acceleration. Several thousand rounds per barrel are projected in military appplications where long range accuracy is critical. For use in a REAM system, the useful lifetime of a barrel would be further extended because small velocity degradations due to barrel wear are unimportant.

For the REAM application, where the gun is operated remotely at low firing rates, liquid propellants can be adapted with a modest development effort. As of this time, the combustion of liquid propellants is subject to hydrodynamic instabilities which can lead to a wide variation in peak combustion pressures, although variation in muzzle velocity is relatively minor. For example, in a gun designed to operate at peak pressures of 45,000 psi, peaks of 80,000 psi will occasionally be generated. This can be overcome simply by designing a heavy breech section for the gun.

Further theoretical and experimental research into liquid propellant combustion is presently in progress and the problem of controlling hydrodynamic instabilities is not considered insoluble (Reference 5).

There is a large volume of literature dealing with gun barrel erosion and cooling of rapid fire guns. For the rates of fire proposed for a high performance REAM system--one round per minute--there is no heating problem. For higher firing rates--at least up to 15 rounds a minute--heating can be controlled by injection of water into the bore between rounds (Reference 6).

There are few data on erosion in liquid propellant guns although tests to date indicate that erosion will be much less severe than in solid propellant guns. Erosion in solid propellant guns is controlled by the use of stellite inserts and chrome plating, both techniques acting on the prime source of erosion: chemical weakening of the bore surface by hot surface reactions and subsequent scouring of the bore by the flowing gases during the launch cycle. Techniques have been developed to permit thousands of rounds to be fired in medium and large bore guns where long range accuracy is important. Inexpensive barrel inserts for medium and large bore guns can be changed in a matter of minutes by one or two men with hydraulic support equipment (Reference 6).

Because of the relaxed requirements of the REAM system (no long range accuracy and remote operation for example), many of the problems encountered in military applications are minor for the proposed mining and tunneling REAM application.

SECTION 4
CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The tunnel experiments carried out at Hope Valley demonstrated that the REAM concept of projectile impact is a most promising and practical approach for improvement of excavation technology in medium to hard rock. A 13-foot-diameter tunnel, representative of the size of many mining and tunneling projects, was driven 26 feet deep into a granitic formation. The amount of rock removed per shot in this tunneling situation exceeded projections based on single impact craters by a factor of three. The specific energy of the projectile impact process during tunneling was 120 ft-lb/in.^{3}.

During the field test, two methods of wall control were demonstrated. It was shown that competent smooth-wall tunnels could be driven when a pre-kerfing method such as line-drilling is employed and that competent tunnel walls with nominal overbreak could be produced with no pre-kerfing when smaller guns are used for trimming. It was also demonstrated that the hazard from ejecta is minor, dust control is possible with a simple water spray-down system, and that the size and spatial distribution of muck is amenable to conventional mucking techniques.

A secondary breakage application of guns for large boulders was shown to be feasible. The advantages of the gun in this role are that large boulders can be fragmented from a considerable distance and that, because there is little throw from the surface impact, heavy equipment need not be moved out of the area.

Because of the flexibility and practicality of the REAM concept, it has a wide application to high-speed tunneling and to many mining and surface excavation operations. In an independent analysis by Jacobs Associates of San Francisco, advance rates of five to eight times those of conventional drill and blast and projected costs of 60 percent those of drill and blast appear possible in high-speed tunneling using the REAM method. Competitive costs for many mining applications are indicated if propellant costs can be minimized.

Finally it is concluded that liquid propellant gun systems offer the most promise for a REAM system. With existing technology, 10 pounds of propellant are capable of accelerating a 10-pound projectile to over 5000 ft/sec which results in the excavation of 1-1/2 tons of hard rock. With some further development several inexpensive liquid-propellant gun systems can be adapted for underground use.

4.2 RECOMMENDATIONS

The next phase in the development of the REAM concept is envisioned as a series of underground tests to demonstrate the controllable underground operation of the critical elements of the system. This would include the design of an acoustic baffle and simple energy damping system to contain the muzzle blast. During these underground tests, the ability of the launcher to drive drifts of varying cross section and to negotiate sharp corners should be evaluated. An interim program should be considered to extend the Hope Valley tunnel another 15 to 30 feet with guns only, using large guns for primary rock breakage and smaller guns for controlling tunnel contour and overbreak.

It is recommended that an effort to select and develop some of the more promising liquid propellants be initiated and subsequently a program to adapt a liquid propellant gun for underground be started. Because of its effect on tunneling economics, an optimization of projectile size, shape, density, and velocity should be carried out in a series of parametric experiments. The feasibility of the REAM concept for certain mining and surface excavations should be further investigated and an evaluation of the economics of the REAM system in these situations should be undertaken.

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APPENDIX A

COST EVALUATION
OF
REAM METHOD
FOR TUNNEL DRIVING

PREPARED FOR

PHYSICS INTERNATIONAL
SAN LEANDRO, CALIFORNIA

BY

JACOBS ASSOCIATES
SAN FRANCISCO, CALIFORNIA

November 2, 1972

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JACOBS ASSOCIATES ENGINEERS AND CONSULTANTS
CONSTRUCTION PERFORMANCE SERVICES

500 SANSOME • SAN FRANCISCO 94111 • TELEPHONE (415) 434-1822 • CABLE: DONJAY

November 2, 1972

Mr. John Watson
Physics International
2700 Merced
San Leandro, California 94577

Dear Mr. Watson:

Enclosed is a report on Cost Evaluation of the Ream method based on 1972 data.

Very truly yours,

JACOBS ASSOCIATES

T.N.Williamson

TNW:jmm
Encl.

TABLE OF CONTENTS

FORWARD

This report is a second updating of cost studies comparing a novel method of Rock disintegration for tunneling with similar tunnels excavated by conventional drill and blast methods. This is an evaluation of an innovation of Physics International called REAM. This estimate reflects new data developed in extensive field tests, just completed in the fall of 1972, by Physics International.

The earlier analyses made by Jacobs Associates in 1970 and 1971 were based, as in this one, on REAM performance and unit cost data furnished by Physics International.

The REAM method fundamentally is disintegration of rock by use of cannons to fire solid concrete projectiles into the rock. This cost analysis concentrates on tunnels but the excavating method may be useful in mining and construction operations other than tunneling. This cost evaluation does not cover other Rock disintegration applications, which might include secondary breaking of rock in surface excavation, shaft sinking, or massive room excavation underground. Massive rooms underground are required in salt mines, underground limestone mines, power plants, hardened defense facilities and some proposed oil shale mining methods among others. Hard rock tunneling has the greatest need for a major improvement in excavation technology at this time.

The recent data achieved by the REAM developers have resulted from firing 10 pound projectiles into massive granite using a 4 inch gun. This provided the developers a basis to increase their earlier estimates for ratio of rock removed to projectile weight. With a muzzle velocity of 5000 Ft/Min. sec the ratio is 300 to 1 for 10 pound 4 inch projectiles and 500 to 1 for the 80 pounds for the 8 inch projectiles.

The accompanying cost analysis is made with a resulting firing rate of something less than the one shot per minute per gun currently envisioned as a very conservatively potential achievable rate by the REAM developers. The reason for the resulting lower firing rate is that the other tunneling systems are not likely to be developed within the next few years to take full advantage of the excavation potential envisioned by the field results of this system.

DISCUSSION

1.0 BACKGROUND

The optional criteria used in the current analysis differs from that used in previous studies for several reasons. Two tunnel sizes considered in this study are 10 and 20 foot size horseshoe shaped as compared to 13 and 18 foot tunnels used in the earlier study. These are slight variations with little effect on the real cost of performance, and is done to bring this analysis into phase with current thinking of other researchers and tunnel planners who are looking forward to tunnel size standardization.

Earlier analyses used limited data and projections from relatively small scale, laboratory tests at Physics International's field laboratory near Tracy, California. Field test just completed in 1972 with 4 inch guns in massive granite, in the Sierra Mountains, lead the Physics International investigators to the conclusion that the criteria for the 1971 estimate were far too conservative.

Part of the earlier estimating efforts was to study effects on cost of rates of fire of the cannon as well as the weight of rock to projectile ratio required to make this system competitive with conventional tunnel driving systems.

In 1971 it seemed reasonable to use a 4 pound projectile and a rock ratio of 100 to 1. The current tests give the investigators confidence in the use of larger projectiles of 10 pounds in a 4 inch gun and 80 pounds in an 8 inch gun, with a 300 to one ratio for the smaller projectile and a 500 to 1 rock projectile ratio for the 80 pound shot.

2.0 PERFORMANCE

2.1 Tunneling Process

A brief description of the proposed tunneling process and its effect on performance and cost is in order. Four cannon will be mounted on a crawler vehicle powered by electricity or diesel which will be operated by remote control. The guns may be cycled to aim automatically or they may be aimed manually as the required firing rate is reasonably slow. The guns will be approximately 60 feet from the face. The forward area will be monitored by television.

The forward gun area will be separated from the operators cabin area by a depressurized sound and pressure barrier. Conveyors and utility lines must go through this barrier. It must have means to permit continuous or occasional forward passage of ground support materials, projectiles and propellants. A slight negative pressure in the forward shield of a few inches of water gage, is envisioned. This will be produced by an industrial blower.

The muck will be loaded onto a self loading flight conveyor. Much of the debris will be thrown on to this conveyor but some of it must be loaded by sweeping arms. Rail haulage with double track all the way from the machine to the portal is included in these estimates for the REAM method. The cars will be loaded by a belt conveyor which will receive the material from the face loader.

2.2 Rate of Advance

The theoretically best rate of continuous advance was computed for 10 foot and 20 foot tunnels using a 4 inch projectile of 10 pounds weight each. These data based on one to four guns firing one round per minute each are shown in table 2.1 using a rock to projectile

THEORETICAL PERFORMANCE OF REAM

TUNNEL ADVANCE PER DAY - 4 INCH GUN - 10 AND 20 FOOT TUNNELS

No. of Guns	Shots Per Hour	Weight Of Rock Dislodged Per Hour 1000 Pounds	Cu. Yd. Rock Removed Per Hour	THEORETICAL ADVANCE 10 Foot Tunnel FT/HR	THEORETICAL ADVANCE 10 Foot Tunnel FT/DAY	THEORETICAL ADVANCE 20 Foot Tunnel FT/HR	THEORETICAL ADVANCE 20 Foot Tunnel FT/DAY
1	60	180	39	9.5	204	2.5	53
2	120	360	78	19.0	408	5.0	107
3	180	540	117	28.5	612	8.0	172
4	240	720	157	38.0	817	10.5	225

NOTES & ASSUMPTIONS

1- Projectile Wt. 10 LB.
2- Rock to Projectile Ratio 300:1
3- WT. Rock Per Cu. Yd. 4600 Pounds
4- Cu. Yd. Rock Per Foot 10FT Tunnel 4.1
5- Cu. Yd. Rock Per Foot 20FT Tunnel 14.9
6- Theoretically maximum hours available per day 21.5
7- One Shot Per Gun Per Minute
8- Rock dislodged by Trim Guns is ignored.

TABLE 2.1

ratio of 300 to 1.

For these studies, solid rock was assumed to weight 4600 pounds per cu.yd. A volume of rock of 3.3 cu.yd. per lin.ft. of tunnel for the 10 ft. tunnel is assumed and 13.2 cu.yd. per lin.ft. for the 20 ft. tunnel. For purpose of analysis this study used 21.5 work hours per day. Rock dislodged by trimming guns is ignored insofar as production is concerned.

Table 2.2 presents the projections of optimum performance of 8 inch guns in a 20 foot tunnel using a rock projectile ratio of 500:1. These guns which fire an 80 pound projectile, are too large for the 10 foot tunnel.

It should be pointed out here that the rock to projectile ratio does not mean that each shot produces a cavity by impact of 300 to 500 times it's weight. Field tests show that considerable rock mass between individual cavities made directly by impact enhances this ratio considerably.

Unfortunately the faster the instantaneous advance rate the greater will be the delays based on cyclic operations. It is necessary to evaluate the REAM method in view of the limitations of the supporting system's capabilities likely to be available in the next 5 to 10 years. Estimates in lost time per day in hours and by cause as well as the total percentages have been analyzed.

Some of the delay causes will be problems in:

Gun Operation
Projectile and Propellant Supply
Muck Handling
Shootings Tights and Bottom
Advancing Utilities
Ground Support and Scaling
Environment

THEORETICAL PERFORMANCE OF REAM

TUNNEL ADVANCE PER DAY - 8 INCH GUN - 20 FOOT TUNNEL

No. of Guns	Shots Per Hour	Weight Of Rock Dislodged Per Hour 1000 Pounds	Cu. Yd. Rock Removed Per Hour	THEORETICAL ADVANCE RATE 20 Foot Tunnel FT/HR	FT/DAY
1	60	2400	522	35	752
2	120	4800	1043	70	1505
3	180	7200	1565	105	2257
4	240	9600	2087	140	3010

NOTES & ASSUMPTIONS

1- Projectile Wt. 80 LB.
2- Rock to Projectile Ratio 500:1
3- WT. Rock Per Cu. Yd. 4600 Pounds
4- Cu. Yd. Rock Per Foot 20FT Tunnel 14.9
5- Theoretically maximum hours available per day 21.5
6- One Shot Per Gun Per Minute
7- Rock dislodged by Trim Guns is ignored.

TABLE 2.2

As stated the higher the instantaneous advance rate causes a higher percentage of time lost in these delays. These analyses indicate that percentage efficiency (or effective time) and resulting advance for planned full time firing in the 10 foot tunnel would be approximately:

No. 4 Inch Guns	Ft/Day Optimum	Time % Effective	Actual Ft/Day
1	204	46	110
2	408	38	200
3	612	19	226
4	817	5	220

As a result 226 feet has been chosen as a goal. As will be discussed, 4 guns will be provided but they need be fired on a continuous basis, with normal delays at only 3/4 the normal optimum rate.

On the same basis the analysis for the 20 foot tunnel was as follows:

No. 8 Inch Guns	Ft/Day Optimum	Time % Effective	Ft/Day
1	752	50	375
2	1505	37	555
3	2257	19	430
4	3010	5	150

In effect two guns firing at an optimum rate will remove rock as fast as the other sub-systems can cope with it. The goal, therefore, has been set at 555 feet per day. Again it has been established that it may well be desirable to have 4 guns but in this case fire them only at one half the rate they would normally be fired.

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3.0 COSTS

3.1 20 Foot Tunnel

A summary of all costs estimated for a 20 foot REAM Tunnel and comparable costs, for a 20 foot Drill and Blast Tunnel are given in Table 3.1.

Using an anticipated average daily advance of 550 foot of unsupported tunnel for REAM and 70 foot for Drill and Blast, an estimate of typical anticipated costs has been prepared. For the purpose of this report average labor cost, including burden is assumed at $12/hour. The labor force for three shifts including tunnel and service crew is estimated at 212 men. This is higher than the 115 man labor force for the conventional drill and blast tunnel since the greater daily advance means more muck trains, rail laying, setting of utility lines, etc. It can be seen however, that the labor cost per linear foot of tunnel is reduced considerably by the increased production.

The item, job materials and supplies in Table 3.1 includes propellant at $0.21/lb. If propellant costs are reduced to: $0.07/lb. (as has been suggested as a possibility) then this item can be reduced to $19.80/lin.ft. or $1.50/cu.yd. and the total costs can be reduced accordingly.

3.2 10 Foot Tunnel

A similar estimate has been prepared for a 10 foot tunnel, with progress for REAM at 226 foot per day and a Drill and Blast tunnel at 65 foot per day. The summary of this estimate is given in Table 3.2.

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ESTIMATED COSTS COMPARISON - 20 FOOT TUNNEL

	REAM @ 550'/Day		DRILL & BLAST @ 70'/Day	
	Cost Per Lin.Ft.	Cost Per Cu.Yd.	Cost Per Lin.Ft.	Cost Per Cu.Yd.
LABOR	$ 37.00	$ 2.80	$158.00	$11.95
JOB MAT'LS & SUPPLIES	42.20	3.20	40.00	3.00
EQUIPMENT OPERATION	9.10	0.70	33.00	2.50
OVERHEAD	14.50	1.10	30.00	2.30
PLANT	32.00	2.40	28.00	2.10
EQUIPMENT WRITE OFF	50.00	3.80	42.00	3.20
	$184.80	$14.00	$331.00	$25.05
MARKUP @ 17%	31.40	2.40	39.00	2.95
TOTAL COST	$216.20	$16.40	$370.00	$28.00

TABLE 3.1

ESTIMATED COSTS COMPARISON - 10 FOOT TUNNEL

	REAM @ 226'/Day		DRILL & BLAST @ 65'/Day	
	Cost Per Lin. Ft.	Cost Per Cu. Yd.	Cost Per Lin. Ft.	Cost Per Cu. Yd.
LABOR	$ 42.00	$12.70	$ 96.00	$29.10
JOB MAT'LS & SUPPLIES	21.95	6.65	14.70	4.45
EQUIPMENT OPERATION	5.60	1.70	16.50	5.00
OVERHEAD	9.75	2.95	24.20	7.35
PLANT	21.80	6.60	20.00	6.05
EQUIPMENT WRITE OFF	28.05	8.50	24.00	7.30
	$129.15	$39.10	$195.40	$59.25
MARKUP @ 17%	21.95	6.65	33.20	10.05
TOTAL COST	$151.10	$45.75	$228.60	$69.30

TABLE 3.2

4.0 CONCLUSIONS

The findings of this analysis are that a very slow firing rate of solid projectiles into rock at something less than one shot per minute with the REAM system provides a capability of advancing a tunnel at competitive rates and costs of conventional methods. This is based on Physics International's new field results of getting a 300 to 1 ratio of rock removed to projectile weight for 10 pound projectiles. From these results they have scaled an anticipated rock to projectile weight ratio for an 8 inch, 80 pound, shot to 500 to 1.

This study used Physics International's projectile and capital machinery costs. This with other ordinary requirements indicates a cost and advance rate shown in Table 4.1 should be a reasonable research goal.

This is based on good ground not requiring roof support or delays due to water or other natural causes. Rail haulage is used in the estimates.

It should be restated that 4 guns are planned for machine design balance and maintenance reserve although 3 smaller 4 inch guns appear to be enough in the 10 foot tunnel and two eight inch guns are enough for the 20 foot.

PIFR-391

REPORT OF INVENTIONS

Physics International Company certifies that there were no inventions conceived or first actually reduced to practice in the work called for under Contract H0220015.

Judith Johnston

Judith Johnston
Contract Administrator

26 February 1973

BACKGROUND PATENT

U.S. Patent #3,695,715

Title:	Rock Fracturing Method and Apparatus for Excavation
Inventor:	Charles S. Godfrey, Berkeley, California
Assignee:	Physics International Company, San Leandro, California
Filed:	April 1, 1970
Granted:	October 3, 1972